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SUPPOSE WE COLLIDE WITH A PLANETOID

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ABSTRACT

A calculation has been made of the kinetic energy that a small planetoid, such as Icarus, would have if it were attracted by the gravitational field of the earth in such a way that it fell onto the earth's surface. This energy is several orders of magnitude larger than the energy released by the largest nuclear device exploded to date and is even more than 100 times the average annual energy released by earthquakes.

Suggestions and comments are presented regarding possible procedures that might be followed should a collision course appear imminent between such a planetoid and the earth.

SUMMARY

Problem:

What do we do if we find that the earth and a small planetoid are on a collision course?

Solution:

Pray, at least for the present. If rockets with a sufficiently large energy capability can be launched as space vehicles and the guidance systems that control their flight made sufficiently accurate, control of the orbits of planetoids may be possible with such vehicles.

PLANETOIDS THAT APPROACH THE EARTH

In 1968 the planetoid (or asteroid) Icarus passes within 4 million miles of the earth. This planetoid is a chunk of matter, probably rock, less than a mile across. It revolves around the sun, just as any other planet, but in a highly eccentric orbit that takes it within the orbit of Mercury at its closest approach to the sun (perihelion) and outside the orbit of Mars at aphelion. While 4 million miles is still a long distance for earthlings, even with our jet-age traffic, it is relatively small from an astronomical point of view, being only somewhat more than 15 times the distance from the earth to the moon.

Icarus is not the only planetoid that has an orbit that extends within the orbit of the earth, although most of the orbits of the known minor planets are in the so-called asteroid belt between the orbits of Mars and Jupiter. Other planetoids that have been observed to pass within the orbit of the earth are Apollo, Adonis, and Hermes, all of which have passed even closer to the earth than Icarus will in 1968. In 1932 Apollo came within 2 million miles of the earth; in 1936 Adonis came within 1.4 million miles; and in 1937 Hermes within 475,000 miles, the latter being only about twice the distance from the earth to the moon.

The distance across each of these objects is in the range from 1 kilometer to 1 mile (1.61 kilometers). The exact size and shape of the very small planetoids are generally unknown because they are observed simply as points of light in the sky and the reflectivity of the surfaces are unknown. Data regarding the orbits of these planetoids and Eros, which also approaches relatively close to the earth but doesn't cross its orbit, are given in Table 1.

Neither Adonis, Apollo, nor Hermes has been observed again since their close approach to the earth. Icarus, however, has been observed a number of times since its discovery in 1949, which was at the time of its most recent very close passage. Small objects are influenced by gravitational forces whenever they pass one of the major planets and may have their orbits changed as a result of the passage. Possibly the three lost planetoids were deflected by the gravitational forces of the earth so that their orbits no longer pass within an easily observable distance.

TABLE 1

Data On Planetoids That Pass Close To The Earth

Planetoid	Size of Planetoid* (miles)	Orbital Characteristics*** Period (years)	Eccentricity	Inclination to Ecliptic (degrees)	Perihelion Distance (A.U.)
Icarus	0.9	1.1	0.83	23.0°	0.18
Hermes**	0.7	2.1	0.63	6.2°	0.62
Adonis**	< 1	2.6	0.76	1.4°	0.43
Apollo**	< 1	1.8	0.57	6.4°	0.64
Eros	10 to 20	1.8	0.22	10.8°	1.14

* The size is an approximate measure of the distance across the planetoid. If spherical, this distance would be the diameter but usually these small planetoids are not of spherical shape.

** These planetoids have not been observed since their passage close to the earth. The orbital characteristics are the best available based on observations at that time. Presumably the close approach to the earth may have perturbed their motion through space.

*** A pictorial description of these orbits can be found in reference 1.

Also, it may be that they are only temporarily lost and will be found again in the future although, if their new orbits are quite different from the old, they may not be recognized as the same objects. Even though the observed orbits of none of these planetoids actually intersect the orbit of the earth at the present time, but pass above or below it, continued changes in their orbits as a result of gravitational perturbations may result in such an intersection at some future time. It is, therefore, in order to ask the question: "What would be the results of a collision between a planetoid of this size and earth?"

OBSERVABLE EFFECTS OF COLLISIONS OF LARGE METEOROIDS WITH THE EARTH

We have considerable evidence that shows the effects produced by an object from space striking the surface of the earth. The large meteor crater near Winslow, Arizona was produced by an iron meteoroid that struck the earth many thousands of years ago.[2] This meteoroid, now known as the Canyon Diablo meteorite, was moving with such a high velocity that its kinetic energy was transformed into a tremendous explosion at the time of impact. If we assume that we can scale in accordance with the empirical rules established by Nordyke[3] to something as big as the Arizona Meteor Crater from the smaller craters produced by chemical and nuclear explosions in desert alluvium at the Nevada Test Site, we can calculate the energy that went into producing that crater. We can then compare this energy with the kinetic energy that an Icarus or a Hermes would have if it collided with the earth and derive some sort of idea regarding the resulting effects. From the scaling of crater sizes, the explosive energy necessary to produce an Arizona Meteor Crater is found[4] to be about 20 megatons of TNT, which is comparable to the yield of the largest nuclear explosion, but without any of the radioactivity that accompanies the detonation of nuclear devices.

Although not as close to home as the Arizona Meteor Crater, the Tunguska meteor fall is much more modern. This meteor entered the atmosphere of the earth in Central Siberia in 1908 and was witnessed by several people in the region.[5] Its interaction with the frictional drag forces of the atmosphere appeared to observers as a tremendous explosion, later determined to have occurred at an altitude of more than 15 km, and to have been comparable to the detonation in modern times of a nuclear device having a yield of several megatons of TNT equivalent. Even today the trunks of many trees that composed vast forests in the region of the Tunguska fall lie where they were

knocked down by the blast, all lying away from the region of detonation. Many pictures have been published of these destroyed forests. Krinov[5] reports that the Tunguska meteor was accompanied by extremely strong optical, acoustical, and mechanical phenomena, which were observed over an area more than 1500 km in diameter in Central Siberia. The fireball streaked across the sky during daylight hours. A thick trail of dust was left along its path. After disappearance of the fireball, deafening explosions occurred, and were heard as much as 1000 km away. At Vanavara, some 60 km south of the place of fall, one of the inhabitants, who was sitting on the porch of a house, was thrown several meters and felt a sensation of heat. Many of the trees that were blown down by the shock waves produced by the meteoroid, were also burned or scorched by the heat that it produced. A seismic wave was recorded by the Irkutsk Magnetic and Meteorological Observatory, 893 km from the epicenter. A barograph as far away as Berlin recorded the effect of the explosion.

The observed effects of the Tunguska meteor fall can be explained if we assume that the object that came into the atmosphere to have been composed of porous matter. Porous meteors of smaller size are relatively well known. Verniani, for example, finds[6] that about 70 percent of the bright photographic meteors are porous bodies having densities between 0.01 and 0.7 g cm^{-3}.

THE ENERGY EXPENDED BY A PLANETOID COLLISION

What energy would be expended in the collision of a small planetoid with the earth? Suppose, for this calculation, that a stone planetoid one mile in diameter simply falls into the earth under the influence of the force of gravitation, such that it attains a velocity of 11.2 km/sec at the time it strikes the surface of the earth. Although these assumptions are hypothetical, they are sufficiently like the conditions to be encountered in a collision with any of the known planetoids that cross the orbit of the earth that they may be viewed as a representation of a typical encounter. A spherical planetoid with a diameter of one kilometer could just as easily have been used as our example. Its volume would have been slightly less than one-quarter the volume of the planetoid that is a mile in diameter. We would then have had to reduce the magnitude of our calculations in accordance with the effects produced by this smaller object. Of course, the planetoid has an orbital velocity prior to

entering the gravitational field of the earth. Thus, under most circumstances, its velocity at the time of reaching the surface of the earth would be greater than 11.2 km/sec. Therefore, for our hypothetical solar-system object, the calculations we undertake represent a minimum energy of collision. The energy expended in the encounter could be much greater. A calculation of the speed of Icarus as it passes the orbit of the earth is given in Appendix A.

If we assume a density $\rho = 3$ g/cm^3 (igneous rock is 2.75 g/cm^3) the total mass of an object one mile (1.609 km) in diameter is $M = 4/3\ \pi\ r^3\ \rho = 6.55 \times 10^{15}$ g. If an object with this mass simply falls to the surface of the earth from a point in space, the kinetic energy W it attains because of the effects of gravitational attraction is $W = 1/2\ m\ v^2 = 1/2(6.55 \times 10^{15})\ (11.2 \times 10^5)^2 = 4.11 \times 10^{27}$ ergs, where v is the escape velocity from the surface of the earth, 11.2 km/sec.

Using a conversion factor of one kiloton equivalent of TNT $= 10^{12}$ calories $= 4 \times 10^{19}$ ergs, this energy is approximately equivalent to 100,000 megatons of TNT, extremely large compared to the 20 megatons estimated as required to produce the Arizona Meteor Crater or the approximately 10 megatons expended at the time of the Tunguska fall. If all of the planetoid were to penetrate through the atmosphere to the surface, the crater it would produce would be about eight miles in diameter, assuming again that the results from the smaller surface explosions can be scaled[3] up to such tremendous energies.

To gain some idea of the extremely large amount of energy associated with such a collision note that Gutenberg estimates[7] that the average total energy released during an entire year by earthquakes is about 10^{25} ergs. Thus, the kinetic energy of our hypothetical planetoid at the time of impact on the earth's surface would be some 100 or more times the average annual energy released by earthquakes.

POSSIBLE SOLUTIONS TO THE PROBLEM OF AN EARTH-PLANETOID COLLISION

No possible danger exists at the present time, but what could we do if such a danger did arise? Three possible solutions come to mind: Evacuate that portion of the earth that would be affected by the direct hit; send up a missile carrying a large nuclear warhead to blow the planetoid apart; or attempt to attach a rocket to the planetoid sufficiently long before it is due to impact against the earth to be able to move it away from a collision course.

The evacuation solution presents a tremendous logistic problem, although not impossible. It could mean the evacuation of and possibly the destruction of one or more entire countries if calculations showed that the planetoid would strike in Europe, Central America, or in other areas in which the area occupied by individual countries is small. If the hit were to occur in an ocean basin, the evacuation of people from all coastal regions bordering that ocean would probably be necessary. Although detailed calculations have not been made, it seems highly probable that tsunamis (tidal waves) would occur that are many times worse than the tsunamis following the Alaska earthquake of March 1964 and the Chilean earthquake of May 1960. The effect of an impact that expends an energy of more than 100 times the energy of either of these earthquakes would probably be felt to a greater or lesser degree by every resident of the earth, since it could very well set up a harmonic vibrational pattern (eigenvibrations) in the mantle and crust of the earth.[c] Even large earthquakes establish weak patterns of this type. Some of these, such as after the Chilean and Alaskan earthquakes, have been observed to continue for several days.[9,10]

The explosive breakup solution sounds quite good at first but may lead to more serious difficulties. Suppose we blow the planetoid into 1,000 pieces of equal mass. Then simply by falling into the earth under the influence of gravitational forces, any one of these pieces would acquire a kinetic energy that is roughly equal to the energy expended by the impact of either Canyon Diablo or Tunguska. Instead of having a single object which we can follow, we now have 1,000 pieces or so, each so small they probably could not be followed. Each may then strike the earth at any time in the future. We must then be prepared to accept the unexpected destruction of a city or other large area, without any advance notice, should one of these chunks of matter stray into the earth's gravitational field. Some of the material would be collected, however, by the moon and by other planets so the total impact energy would be greatly reduced. Furthermore, the dissipation of the energy would be spread over a relatively long period of time, probably many centuries. This series of smaller impacts could never lead to such disastrous results as those produced by the impact of the entire planetoid. Because of the long term effects of these smaller impacts, a decision affecting many future aspects of life on earth might be in the offing should use of a nuclear warhead, or impact of the planetoid, turn out to be the only available alternate solutions.

If it can be done, the deflection solution would be the most satisfactory for then we would have a control over the planetoid and furthermore could prevent any part of it from ever striking the earth. But then how much energy would be required to push the planetoid away from a collision course with the earth? If we assume our hypothetical planetoid travels in an orbit having the same characteristics as that of

Icarus, as given by Richardson,[1] we probably can never accumulate enough large rockets to push the planetoid away from a head-on collision with the earth. Calculations showing the type of rocket needed if it is attached 10 million miles from the earth are given in Appendix B. If a large enough rocket is not available, we may have to revert to one of the other, possibly less satisfactory, solutions.

Besides the huge energy requirements, the problems of attaching a rocket for moving the planetoid or an explosive for breaking-up the planetoid are rather tremendous. Attachment during the final approach of the planetoid on its collision course may be too late for, if attachment is made during the collision orbit, the rocket would have to be launched early enough to attach to the planetoid many tens of millions of miles from the earth, so that the nudge given the planetoid would be enough to deflect it away from a collision course. The guidance system would have to be really of superior quality to be able to attach the rocket to an object only a mile or less across at a distance of several million miles and moving at such high speeds. If possible, it might be preferable to try to attach during an earlier revolution of the planetoid. The period of the known planetoids that come within the earth's orbit are all slightly more than a year so they pass relatively frequently, but they may pass the earth's orbit at very large distances from the existing position of the earth at the time.

If the orbital motion of the planetoid and that of one of the major planets other than the earth were found to follow appropriate paths, the possibility may arise that the planetoid could be forced into a collision with the other planet, thereby removing forever the danger of a future earth-planetoid collision.

APPENDIX A

CALCULATION OF THE SPEED OF ICARUS AS IT CROSSES THE ORBIT OF THE EARTH

To be able to conserve energy as a planetoid moves in an elliptical orbit around the sun, the sum of the kinetic and potential energies of the planetoid must remain constant throughout its orbit, such that

$$\frac{1}{2} mv_a^2 - \frac{GMm}{r_a} = \frac{1}{2} mv_p^2 - \frac{GMm}{r_p} \qquad (1)$$

where v_a and r_a are, respectively, the speed of the planetoid and its radial distance from the sun at aphelion, v_p and r_p are the corresponding quantities at perihelion, m is the mass of the planetoid, M the mass of the sun, and G the gravitational constant. For Icarus perihelion is 1.7×10^7 miles (= 2.74×10^{12}cm) from the sun, as given by Richardson,[1] and aphelion is at 1.83×10^8 miles (= 2.95×10^{13}cm). The eccentricity of the orbit of Icarus is $\epsilon = 0.83$. The difference between the squares of the velocities of the planetoid at perihelion and aphelion are then

$$v_p^2 = v_a^2 = 2GM \left(\frac{1}{r_p} - \frac{1}{r_a} \right), \qquad (2)$$

which for Icarus is

$$v_p^2 - v_a^2 = 2\ (6.67 \times 10^{-8})\ (1.97 \times 10^{33}) \left(\frac{1}{2.74 \times 10^{12}} - \frac{1}{2.95 \times 10^{13}} \right) = 8.70 \times 10^{13} \qquad (3)$$

Because the radius vector of an object in an elliptical orbit under the influence of a central force sweeps out equal areas in equal time (Kepler's law of equal areas):

$$r^2 \, d\theta/dt = rv_{\perp} = 2c \tag{4}$$

where $v_{\perp}$ is the component of velocity at right angles to the radius vector and c is a constant. Thus:

$$v_{\perp}^{\,2} = 4c^2/r^2 \tag{5}$$

and, since the velocities of the planetoid at both aphelion and perihelion are composed entirely of the component vertical to the radius vector, the constant c can be evaluated from

$$v_p^2 - v_a^2 = 4c^2 \left(\frac{1}{r_p^2} - \frac{1}{r_a^2} \right) \tag{6}$$

such that $4c^2 = 8.70 \times 10^{13}/1.321 \times 10^{-25} = 6.59 \times 10^{38}$ and $2c = 2.57 \times 10^{19}$. At perihelion then $v_p = 2c/r_p = 2.57 \times 10^{19}/\ 2.74 \times 10^{12} = 9.36 \times 10^6$ cm/sec and at aphelion $v_a = 2c/r_a = 2.57 \times 10^{19}/2.95 \times 10^{13} = 8.70 \times 10^5$ cm/sec. Thus the kinetic energy at perihelion is $\frac{1}{2}\, mv_p^2 = \frac{1}{2}\,(6.55 \times 10^{15})\ (8.76 \times 10^{13}) = 2.87 \times 10^{29}$ ergs and at aphelion is $\frac{1}{2}\, mv_a^2 = \frac{1}{2}\,(6.55 \times 10^{15})\ (7.57 \times 10^{11}) = 2.48 \times 10^{27}$ ergs. At intermediate points in its orbit, the velocity and corresponding kinetic energy has intermediate values, determined by the equation for the radius vector of the ellipse

$$r = \frac{a\ (1 - \epsilon^2)}{1 + \epsilon \cos\theta} \tag{7}$$

where a is the magnitude of the major semiaxis, ϵ the eccentricity, and θ the angle the radius vector makes with the direction of perihelion. Using the differential $d(u/v) = (v\ du\ \ u\ dv)/v^2$, $dr/d\theta$ for an ellipse, eq. (7), is

$$\frac{dr}{d\theta} = \frac{-a(1 - \epsilon^2)\ (-\epsilon \sin\theta)}{(1 + \epsilon \cos\theta)^2} = \frac{a\epsilon \sin\theta\ (1 - \epsilon^2)}{(1 + \epsilon \cos\theta)^2} . \tag{8}$$

Because, from the law of equal areas, $d\theta/dt = 2c/r^2$,

$$\frac{dr}{dt} = \frac{dr}{d\theta}\frac{d\theta}{dt} = \frac{2ac\epsilon \sin\theta\ (1-\epsilon^2)}{r^2\ (1+\epsilon \cos\theta)^2} . \tag{9}$$

The distance between the earth and the sun is 93×10^6 miles and the major semiaxis of the elliptical orbit of the planetoid is 10^8 miles so, for the planetoid approaching the earth from the direction of aphelion at a distance of 10 million miles from the earth, $r \approx a$ and $\cos\theta = \left[(1 - \epsilon^2) - 1\right]/\epsilon$. Thus $\cos\theta = -\epsilon = -0.830$ and $\sin\theta = -0.558$ for the condition that the magnitude of the eccentricity is that of the orbit of Icarus, $\epsilon = 0.830$. From eq. (10) $dr/d\theta = (1.61 \times 10^{13})$ $(0.83)\ (-0.558)\ (0.311)/\left[1 + (0.83)\ (-0.83)\right]^2 = -2.40 \times 10^{13}$ cm/steradian, and from eq. (6) $d\theta/dt = 2c/r^2 = (2.57 \times 10^{14})/(1.61 \times 10^{13})^2 =$ 9.91×10^{-8} steradian/second. Then $dr/dt = (dr/d\theta)(d\theta/dt) =$ $(-2.40 \times 10^{13})\ (9.91 \times 10^{-8}) = -2.38 \times 10^6$ cm/sec and $r\ d\theta/dt = (1.61 \times 10^{13})\ (9.91 \times 10^{-8}) = 1.60 \times 10^6$ cm/sec.

The speed of the planetoid at this point is

$$v = \left[\left(\frac{dr}{dt}\right)^2 + r^2 \left(\frac{d\theta}{dt}\right)^2 \right]^{1/2}$$

$$= \left[(2.38)^2 + (1.60)^2 \right]^{1/2} \times 10^6 = 2.87 \times 10^6 \text{cm/sec} \qquad (10)$$

and its kinetic energy is $\frac{1}{2} mv^2 = \frac{1}{2} (6.55 \times 10^{15}) (8.21 \times 10^{12}) = 2.69 \times 10^{28}$ ergs. The time required to travel the 10 million miles to the earth at this speed is $t = (1.61 \times 10^{12})/(2.87 \times 10^6) = 5.62 \times 10^5$ seconds, which is very nearly 156 hours.

APPENDIX B

CALCULATION OF THE ROCKET SPECIFICATIONS REQUIRED FOR PUSHING OUR HYPOTHETICAL PLANETOID AWAY FROM A COLLISION COURSE WITH THE EARTH

If an impulse is applied to the planetoid in a direction perpendicular to its earthward direction of motion when it is 10 million miles from the earth, this impulse must be of sufficient magnitude to move the planetoid away from a collision course in the 156 hours between application of impulse and time of collision. The radius of the earth, 6,370 km = 6.37×10^8 cm, is the maximum displacement of the planetoid from its original trajectory that should be required, and then only if the planetoid is traversing a dead-center collision course with the earth. If the collision is not dead-center and we are capable of positioning our rocket in such a way that it pushes the planetoid away from a collision with the earth, a smaller energy is required. Of course, under these latter circumstances, if we get the direction of push oriented incorrectly, we may find ourselves pushing the planetoid in the direction of a dead-center collision rather than away from it. This problem may become especially difficult if the planetoid is rotating on an axis. Another factor to be considered is that, the farther away from the earth our rocket can give its push to the planetoid, the smaller the amount of energy that is required. But, the farther we go from the earth the better the precision needed in the guidance system that attaches the rocket to the planetoid. The solution to such a problem is not simple.

In our calculation of the energy that a rocket must provide to accelerate the planetoid sufficiently to make it miss the earth, we need consider only the gravitational field of the earth and calculate the hyperbolic orbit the planetoid traverses relative to the earth. The reason we can make this approximation is that the orbital speed of the planetoid around the sun changes only by a few percent in the 10 million miles from the point of acceleration to its passage of the earth and its orbit has only a very small amount of curvature. Under differing conditions, consideration of the orbital motion of the planetoid may have to be made in this type of calculation. Since, however, the example in this discussion is hypothetical, the simpler calculation is all that is needed to give order of magnitude numerical answers.

The kinetic energy acquired by the planetoid because of the gravitational field of the earth is simply the potential energy it loses in approaching the earth from an infinite distance;

$V(r) = \int_{\infty}^{r} F dr = \int_{\infty}^{r} GmM_e dr/r^2 = -GmM_e/r \Big]_{\infty}^{r}$ where M_e is the mass of the earth. At the instant of acceleration $r = 10^7$ miles $= 1.609 \times 10^{12}$ cm and at the surface of the earth $r = 6.37 \times 10^8$ cm. The quantities G, m, and M_e are all constants. Thus, when the planetoid is separated from the earth by 10^7 miles, the kinetic energy it has acquired because of falling toward the earth under the influence of grativation attraction is only $(6.37 \times 10^8)/(1.609 \times 10^{12}) = 3.96 \times 10^{-4} = 0.0396$ percent of the kinetic energy it will have acquired when it strikes the earth. Therefore, we can assume that its component of velocity in the direction of

the earth, v_x in Fig. 1, at a distance of 10 million miles is entirely the velocity it has because of its orbital motion around the sun. This is, by eq. (10), 2.865×10^6 cm/sec. To get the planetoid to pass the earth without contact, it must be given a velocity v_y such that it passes the earth in a hyperbolic orbit with a velocity at perihelion, v_p, such that

$$\frac{1}{2} mv_o^2 - GM_e m/r_o = \frac{1}{2} mv_p^2 - GM_e m/r_p, \; v_y^2 = 4c^2/r_o^2, \text{ and } v_p^2 = 4c^2/r_p^2 , \qquad (11)$$

where the letters v_o, v_x, v_y, v_p, r_o and r_p are defined in Fig. 1, and G, M_e, m and c are defined earlier in the text. Now, because $v_o^2 = v_x^2 + v_y^2$, eq. (11) becomes $v_x^2 + v_y^2 - v_p^2 = 2GM_e\left[(1/r_o)-(1/r_p)\right]$, and $v_y^2 - v_p^2 = 2(6.67 \times 10^{-8})(5.983 \times 10^{27})\ (6.215 \times 10^{-13} - 1.570 \times 10^{-9}) - 8.208 \times 10^{12} = -9.46 \times 10^{12}$. Substituting this value into the equation $v_y^2 - v_p^2 = 4c^2\left[(1/r_o^2) - (1/r_p^2)\right]$, which is determined from the law of areas, $4c^2 = (-9.460 \times 10^{12})/(-2.465 \times 10^{-18}) = 3.383 \times 10^{30}$ and $2c = 1.959 \times 10^{15}$. Thus $v_y = 2c/r_o = (1.959 \times 10^{15})/(1.609 \times 10^{12}) = 1.218 \times 10^3$ cm/sec.

An impulse must be applied by the rocket to the planetoid to give it the necessary component of velocity, v_y. To give the planetoid an impulse, enough propellant must be expelled by the rocket to conserve momentum within the system. The propellant momentum depends on the temperature of the exhaust gas of the rocket as well as the molecular mass of the propellant material. We calculate the momentum, mass, and kinetic energy of the propellant both for a nuclear rocket, assuming the propellant to be hydrogen and for a chemical rocket, assuming the

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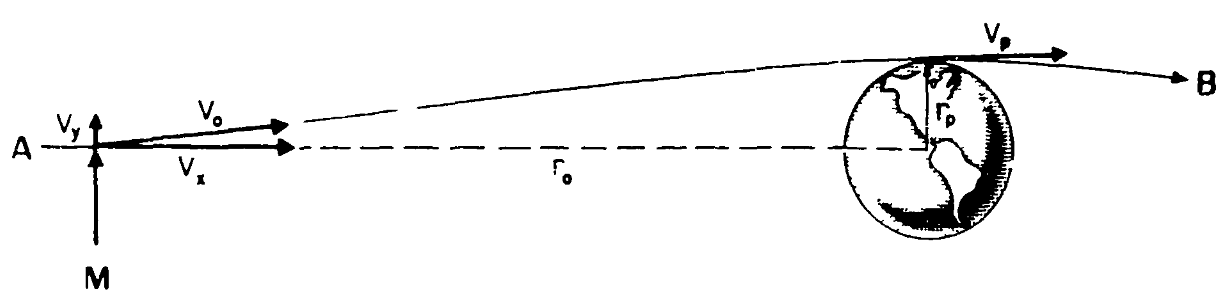

Fig. 1. Schematic illustration to accompany the textual discussion of the change in orbital motion of a planetoid produced as a result of the acceleration provided by a rocket M. The trajectory of the planetoid is changed in this illustration from that of a head-on collision (dashed line) to a course that just misses contact with the earth (fine line from A to B). Vertical dimensions in this figure have been magnified about 1000 times relative to the horizontal dimensions.

propellant molecule to have a mass of 16 atomic mass units.

A typical nuclear rocket operates at about $2300^{\circ}K$, so the average energy for each molecule in the propellant is $kT = (1.38 \times 10^{-16}\ \mathrm{erg\ deg}^{-1})(2300^{\circ}K) = 3.17 \times 10^{-13}$ erg. Since the mass of a hydrogen molecule is 3.34×10^{-24} g, the average speed of a hydrogen molecule emitted from the rocket exhaust is

$$v = (2kT/m)^{1/2} = (6.35 \times 10^{-13}/3.34 \times 10^{-24})^{1/2} = 4.36 \times 10^{5}\ \mathrm{cm/sec.}$$

and the momentum of the individual molecule is

$$p = mv = (3.34 \times 10^{-24})\ (4.36 \times 10^{5}) = 1.46 \times 10^{-18}\ \mathrm{g\ cm/sec.}$$

The momentum of the planetoid in the y direction, based on an assumed speed of 1.22×10^{3} cm/sec, as calculated above, is

$$p = mv = (6.55 \times 10^{15})\ (1.22 \times 10^{3}) = 7.98 \times 10^{18}\ \mathrm{g\ cm/sec.}$$

Thus the number of hydrogen molecules that must be emitted from the rocket exhaust to conserve momentum is $N_H = (7.98 \times 10^{18})/(1.46 \times 10^{-18}) = 5.48 \times 10^{36}$. Since the mass of each hydrogen molecule is 3.34×10^{-24}g, the total number of grams of hydrogen that must be used as rocket fuel is $(3.34 \times 10^{-24})\ (5.48 \times 10^{36}) = 1.83 \times 10^{13}$g. The total kinetic energy of the propelled hydrogen is then

$$W_H = \frac{1}{2}\ (1.83 \times 10^{13})\ (1.90 \times 10^{11}) = 1.74 \times 10^{24}\ \mathrm{ergs.}$$

A typical exhaust temperature for a chemical rocket is somewhat higher than for a nuclear rocket, being more nearly $3600^{\circ}K$. In this case the average energy per molecule is $kT = 4.97 \times 10^{-13}$ erg. If the propellant molecule is assumed to have a mass of 16 atomic mass units (2.66×10^{-23} g), its speed when it has a kinetic energy of

4.97×10^{-13} erg is $v = (9.94 \times 10^{-13}/2.66 \times 10^{-23})^{1/2} = 1.93 \times 10^{5}$ cm/sec., and the momentum of each molecule is $p = 5.15 \times 10^{-18}$ g cm/sec. The number of molecules required to provide the needed momentum is $7.98 \times 10^{18}/5.15 \times 10^{-18} = 1.55 \times 10^{36}$, and their total mass is $(2.66 \times 10^{-23})(1.55 \times 10^{36}) = 4.12 \times 10^{13}$ g. The total mass required for the chemically propelled rocket is thus 2.25 times the mass required for the nuclear propelled rocket. Had the exhaust temperatures of the two rockets been assumed the same, this ratio would have been $8^{1/2} = 2.83$. Thus, even with the temperature advantage for the chemical rocket, the nuclear rocket offers a propellant mass advantage.

The total kinetic energy that the chemical propellant must be given is $W = \frac{1}{2} mv^2 = 5.55 \times 10^{23}$ ergs. The total energy required in this case is less than with the hydrogen propellant but only by a factor of two, and in either case the total amount of energy is enormous, being greater than 10^{10} kilowatt-hours, which is more than the total yearly output of the Hoover Dam hydroelectric plant when operating at full capacity.

To determine the volume of propellant that must be used in the rocket, note that 1 liter of liquid hydrogen has a mass[11] of 272 g. Thus 1 gallon of liquid hydrogen, which is 3.7853 liters, has a mass of 1030 g, and the 1.83×10^{13} g of liquid hydrogen needed as propellant would be 10^{10} gallons, far in excess of the amount of propellant in any of the present-day rockets used in space research.

Even though the calculation that is completed in the preceding paragraph shows that a tremendous amount of energy must be expended to move the planetoid away from a collision with the earth, the kinetic energy imparted to the planetoid of mass 6.55×10^{15} g is only $\frac{1}{2}(6.55 \times 10^{15})(1.22 \times 10^{3})^{2} = 4.86 \times 10^{21}$ ergs, or 1.35×10^{8} kilowatt-hours, which is a little more than the output of 100 hours of full capacity operation of the Hoover Dam hydroelectric plant. If the energy of a nuclear explosive could be channeled so as to break the planetoid into two equal parts, a device with a yield of slightly more than 100 kilotons equivalent of TNT could prevent a collision, for then momentum could be conserved by sending the two halves of the planetoid around opposite sides of the earth. Breaking the planetoid into two equal parts is probably not very easily accomplished, but breaking into two unequal parts might be possible, so the energy needed to prevent a head-on collision probably has some intermediate value between 4.86×10^{21} ergs and 1.74×10^{24} ergs.

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13 ABSTRACT

A calculation has been made of the kinetic energy that a small planetoid, such as Icarus, would have if it were attracted by the gravitational field of the earth in such a way that it fell onto the earth's surface. This energy is several orders of magnitude larger than the energy released by the largest nuclear device exploded to date and is even more than 100 times the average annual energy released by earthquakes.

Suggestions and comments are presented regarding possible procedures that might be followed should a collision course appear imminent between such a planetoid and the earth.

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